4

OUR EXPANDING UNIVERSE*

* Donovan Astronomical Trust Lecture

By Bart J. Bok

The well-known Dutch astronomer, Willem de Sitter, who was my first teacher at Leiden University, was one of the men who had much to do with the birth of the relativistic theory of the Expansion of the Universe. He said in one of his public lectures in the early 1930's that the great development of the first third of our century was not the discovery of the Expansion of the Universe of Galaxies, but rather the Expansion of our Knowledge of the Universe. This is my theme for a lecture delivered toward the end of the second third of our century.

A Bit of History

Today most people do not realize—and those who should often forget—how very little we knew, at the turn of the century, of the depths of our universe. By the year 1900, we were still several years short of the development (by Frank Schlesinger) of the modern precision techniques for the measurement of stellar parallaxes and distances. Spectral classification was still in its infancy and there was no clear concept yet as to the manner in which spectral features might be used for the approximate fixing of the intrinsic brightnesses of the stars, thus permitting us to fix their approximate distances. The measurement of stellar radial velocities was just coming into its own (W. W. Campbell) and the great catalogue of stellar positions and proper motions of Lewis Boss was still in the making. To be truthful, I must say that by the year 1900 astronomers had no real knowledge of stellar distances greater than 50 light years from the sun.

By 1924, when I entered astronomy professionally, the whole picture had changed. The trigonometric method for the measurement of stellar distances had reached its present-day accuracy, which permits us to determine with some degree of confidence, by direct triangulation, distances to 300 light years from the sun. We had available for research reliable catalogues of positions, proper motions, radial velocities, spectral types and apparent magnitudes for a large number of stars, and J. C. Kapteyn's Plan of Selected Areas (1904) had begun to bear fruit in terms of many useful catalogues reaching to faint stars in specially selected fields.

Accompanying this steady accumulation of data, there had come also an increased insight into the arrangement of our universe. The discovery by Kapteyn of the phenomenon of star streaming among the nearer stars (1904) had shown that their motions were probably governed by forces originating beyond the immediate vicinity of our sun. Harlow Shapley (1918) had demonstrated irrefutably from his studies of globular star clusters that our sun is a star in the outskirts of our home galaxy, the Milky Way System; we now know the sun to be located at a distance of 27,000 light years from the centre of our galaxy. Finally, Hubble's work (1922) on the spiral nebula in Andromeda, Messier 31, and other spirals showed these objects to be galaxies like our own Milky Way System, true galaxies with distances of 2 million light years or more from our sun and earth. The stage was thus set for

the acceptance of the startling phenomenon of the general expansion of the universe of galaxies, which had seemed indicated ever since V. M. Slipher (1912) had first noted the gradual increase in the amount of the redshift with faintness (distance) of the galaxies.

During the 1920's and 30's we witnessed a steady march forward in the exploration in depth of our universe. The cepheid variable star reigned supreme as a standard for the measurement of great distances, and few were the astronomers who doubted the general validity of the 'law' establishing a relation between the period of light variation of a cepheid variable and its intrinsic brightness which we now know most certainly not to be universal. Bertil Lindblad and Jan H. Oort discovered the effects of general galactic rotation (1926), thus confirming the eccentric position of our sun in relation to the centre of our galaxy and they showed that our sun, moving around the centre at a rate of the order of 140 miles per second, takes 200 million years to complete one circuit. An important discovery of the early 1930's was that of the general absorption of light near the central plane of our galaxy (R. J. Trumpler 1930) and, finally, it was during the 1930's that radio astronomy entered the picture (Karl Jansky and Grote Reber 1931) almost unnoticed.

In the years following World War II, there came the general realization (Walter Baade) that there was more than one variety of cepheid variable and that the accepted distance scale for galaxies in the universe, which had seemed a reasonably firm one in the late 1930's, was probably in error—with all estimated distances too small by factors 3 or 4. This suspicion has been amply confirmed by the researches of the past decade. The Hubble Constant, which measures the velocity of recession in kilometers per second at a distance of one million parsecs (3·26 million light years) was in the early stages estimated to be possibly as high as 500, whereas by now values in the range 75 to 125 are generally quoted. One should bear in mind that a quadrupling of the scale of the universe is not a minor matter, for it implies a decrease by a factor $4^3 = 64$ in the estimated density of matter in the universe—that is, provided all other estimated quantities stay put.

The Hubble Constant is a very basic quantity for the study of our universe. From the measured redshift in the spectrum of a distant galaxy, we can obtain a good value for the observed velocity of recession of that galaxy. From this observed velocity we can obtain an approximate value for the distance to the galaxy, provided we know the value of the Hubble Constant. It is in this manner that we estimate the distance to the farthest known single galaxy. Two years ago, Rudolph Minkowski measured the redshift for a faint galaxy that he suspected to be very far distant from the sun. The recessional velocity corresponding to the observed redshift proved to be equal to about 140,000 kilometers per second, 46% of the velocity of light. The estimated distance of this object is betwen 4 and 5 thousand million light years. We see this object as it was 4 to 5 thousand million years ago, which is about the time when our solar system was formed.

The Hubble Constant plays a very important part in attempts to establish the probable age of the universe. Let us for a moment accept the hypothesis that our universe of galaxies originated at some time in the past from a much more compact unit and that in the observed general expansion we are witnessing the after-effects of a giant explosion often referred to as the 'Big Bang'. Let us forget for the moment about relativistic complexities and calculate the approximate time interval that has elapsed since the beginning of the expansion. Some elementary arithmetic suffices to show that, to a velocity of one kilometer per second, there corresponds a distance travelled of close to one parsec (3·26 light years) in one million years. If two

galaxies are rushing away from each other at the rate of 100 kilometers per second, their distance apart will hence increase at the rate of 100 parsecs in one million years; this distance would increase to one million parsecs in 10 thousand million years. The observed value of 100 for the Hubble Constant suggests therefore that the galaxies of our universe have been running away from each other for at least 10 thousand million years, and this represents the order of magnitude of the age of our universe on the 'Big Bang' hypothesis. I should warn the reader that the argument breaks down if we consider the alternative hypothesis of continuous creation—according to which the universe is an expanding one of constant average density, with newly-created matter replacing that lost in the expansion and in which the process of the formation of new galaxies is an ever continuing one.

The Exploration of Space

The Space Age is with us, but this most emphatically does not imply that the conventional techniques of astronomical research are by now outdated and that henceforth we shall go to the stars directly. The arrival of the Space Age, which was ushered in by the successful launching of Sputnik I in October 1957, holds much promise for the development of astronomy. It means that we shall be able, if we wish, to travel through the solar system, visit the moon, Mars (see Pl. V) and one or two additional planets and their satellites and possibly return home with samples. It means that we shall be able to have a close look at the remaining planets and satellites and we may be able to probe into the secrets of what is underneath the thick atmospheric clouds of ammonia and methane in Jupiter and Saturn, or explore the more controversial cloud cover of Venus. It means, furthermore, that we shall be able to free ourselves from the disturbing effects of the earth's atmosphere, which has hindered in the past our attempts to study properly the ultraviolet and the infrared parts of the spectrum, and which produces bothersome lack of definition in the optical telescopes used at terrestial observatories. The space observatory holds great promise for the future.

We must not delude ourselves and think we shall be able to travel to the stars. The terrific distances involved in the exploration of space are far too little appreciated. The distance from the earth to the sun is 93 million miles, which is a figure that most of us find it impossible to imagine. To bring it a little closer home, bear in mind that it represents 1000 times 93,000 miles: I think that most owners of automobiles have a fair idea how far is 93,000 miles. In the present state of the art of satellite launching, it is considered quite a feat to get one that travels from the earth to the moon in 48 hours. If we had a satellite that would cover the distance to the moon in one hour, that object would take close to two weeks to reach the sun. It would take a little less (say 10 days) to reach Mars or Venus under reasonably favourable conditions, but the trip to Jupiter would take already 8 weeks, that to unimposing Pluto one and a half years. A little arithmetic shows that the trip to the nearest bright star—Alpha Centauri, one of the pointers to the Southern Cross, about 4 light years away—would take approximately 15,000 years, double if the space traveller wishes to return and report on his findings to the home folk.

For the exploration of the universe of stars and galaxies, space research will have the important assignment of providing astronomers with space platforms, which may be used for the purpose of mounting telescopes with the very best optical and tracking properties. Designs for these platforms, with telescopes to match, are already on the drawing board and it is not unlikely that a 50-inch reflector will be sent in orbit by the end of the present decade. The basic problem of precision pointing

of the telescope on any desired spot in the heavens will probably be solved by providing two small auxiliary telescopes that may be locked in position on bright stars, and with reference to which the large reflector will be positioned. The optics of the space telescope will have to be of the highest calibre, for the performance of the instrument will be determined by its optical and mechanical perfection, unaffected as it will be by the disturbing effects produced in terrestial telescopes by the earth's atmosphere. The information gathered by space telescopes will be relayed back to receiving stations on earth by television and telemetric techniques. In other words we shall not need any of the so-called 'break-throughs' before we shall be able to proceed.

The first space observatory will probably be circling the earth in a 24-hour orbit at a height of approximately 22,500 miles, which will mean that it can remain in communication with a single receiving station below it on earth for as long as desired. Parenthetically, these are the altitudes and orbits currently envisaged for some communication satellites, which will hang above the earth as giant reflectors for radio telephonic and television transmissions.

In the United States, there are already in the advanced planning stage several astronomical projects involving the use of earth satellites. In addition to the 50-inch space telescope to which we made reference, there is a major project under way at Princeton University for the design and construction of a spectrograph, which is to be used for high-resolution spectroscopy of stars and nebulae in the far ultraviolet. At the University of Wisconsin, astronomers are building apparatus for the measurement in the ultraviolet of the brightnesses and colours of stars, and at the Smithsonian Institution an extensive programme of mapping the sky in the ultraviolet is well under way.

We should bear in mind that rockets and balloons will continue to play an important role in the exploration of space. Our present knowledge of the cellular structure of the sun's atmosphere has come from balloon flights, which have also contributed much to our knowledge of cosmic rays. Australia is deeply involved in rocket investigations and we are fortunate to have at Salisbury and at Woomera the personnel and the equipment that permits us to do work of the highest calibre in this field. One recent joint U.S.A. and Australian series of rocket flights from Woomera is giving us much interesting information about the ultraviolet properties of stars and nebulae in the southern hemisphere. The principal Australian effort in astronomical space research is now under way at the University of Adelaide and our participation in the joint European plans holds great promise for the future.

Structure and Evolution: The Galaxy and the Magellanic Clouds

The expansion of our knowledge of galaxies and their components is progressing in three interrelated directions. First, we are gradually completing our picture of the universe as a whole and of its component galaxies. Second, we are penetrating further into an understanding of the birth and evolution of the galaxies and we are learning much that is new about the manner in which stars have been formed in the past and are still being formed today from clouds of interstellar gas and dust. And, third, we are gradually beginning to get a clearer picture of the processes of evolution of the stars.

We are progressing in a satisfactory manner with the exploration of our own galaxy, the Milky Way System. It is a flattened galaxy with a diameter of the order of 100,000 light years and with a total mass equivalent to that of 100 thousand million suns, most of it contained in stars. Our sun, a pretty average star as stars go, has a position close to the central plane of our disc-shaped galaxy and is at a

distance of about 27,000 light years from the centre. The star clouds in Sagittarius, which pass overhead at latitudes 30° S., mark the direction to the centre of our galaxy. To study these central regions properly, the optical or radio astronomer should preferably have his observatory located at the latitudes of Australia, New Zealand, South Africa or South America. Pl. VI shows an example of onc of the 5 celestial objects observable only from the southern hemisphere—the globular star cluster 47 Tucanae.

Optical and radio techniques combined are being applied successfully to the delineation of the structural pattern of our galaxy. The clouds of interstellar gas and the associations of young stars are concentrated along some tightly-wound spiral arms, which can now be traced between distances of 10,000 to 50,000 light years from the centre of our galaxy. But the precise tracing of these spiral arms, which is done by the combined efforts of optical and radio astronomers, has run into considerable difficulties. The point of observation in our galaxy to which the sun and earth have been relegated is a most unfavourable one. The optical astronomer is literally fogbound by the ever-present cosmic dust, which is intermingled with the interstellar gas all along the galactic circle. This cosmic fog does not bother the radio astronomer, but he is hampered in his studies by the absence of an independent distance scale and his approach toward a definitive solution of the spiral structure problem does not appear like a simple and straightforward one either. But then, why despair? Thirty years ago most astronomers, the author being one of them, saw little hope that we would even make a start during our lifetimes on obtaining a fair idea as to how the spiral arms of our galaxy run. And here we find ourselves in the early 1960's and we have a first rough picture available. This has come about for three reasons. First, in the late 1940's, Walter Baade showed unambiguously that the spiral arms in galaxies outside our own could be traced through clouds of interstellar gas and associations of young blue-white stars. This was followed by the first successful attempt to trace the spiral arms of our own galaxy (W. W. Morgan and associates in 1951), and finally the radio astronomers at Leiden and at Sydney produced their now famous diagrams (1952 and 1953). In the years to come, the principal advances in our knowledge of our galaxy should come from southern hemisphere observatories, for the key to the solution of the complex spiral structure for the inner parts of the galaxy seems to be the study of the sections of the Milky Way with most southerly declinations. Pl. VII shows one of these sections.

In recent years much attention has been given to the properties and the behaviour of the gas in our galaxy. We do not really know why it is that the interstellar gas shows preference for being concentrated in the spiral arms and avoids the regions in between. To complicate the picture, there are now indications that the spiral arms and the gas in them (but not the stars) expand outward in the plane of the galaxy, away from the centre, but we have no good idea about the forces that are at work. The whole scheme of gas motions and development of spiral arms is complicated by the fact that all of our galaxy, with its wafer-thin central layer of gas and dust, is embedded in an extremely tenuous, roughly spherical gaseous halo. We must discover the cause of these peculiar rules of gas distribution and development. It has been evident for more than a decade that spiral arms can in no way be considered permanent features. They come and go in time intervals of the order of two or three galactic revolutions, say 500 million years, which is only one-tenth of the age of our sun and earth. We must try to understand how and why the spiral arms behave as they do, for it is in these cosmically short-lived features that we find the places where the stars have been born, and are being formed even today.

During the past 15 years, there has been much advance in our knowledge of the processes by which stars are made and evolve. We actually see projected against the beautiful emission nebulae numerous roundish, dark nebulae, globules, which are probably small clouds of gas and dust in the pre-stellar stage. Some of these complexes of dark nebulosity are very fine in appearance, the Horse Head Nebula (Pl. VIII), for instance. Also, near certain large dark nebular complexes, we find tenuous stars which, judged by their spectra and characteristic variability, were formed quite recently on the cosmic scale. Calculation shows that the most rapid evolution will be experienced by gas clouds with masses of the order of 10 to 50 solar masses, which should settle down to become respectable stars in times of the order of one million years. Cosmically speaking this represents a very short time interval, since the age of our sun and earth is probably 5000 times as great and since one galactic revolution takes 200 million years for a star like our sun.

In a way the most spectacular recent expansion of our knowledge has come from observational and theoretical studies of stellar interiors and from related work on stellar evolution. Observationally we have progressed especially because of novel applications of photoelectric precision techniques to the measurements of star colours and brightnesses, which make use of colour filters of various bandwidths. Theoretically, our understanding of the internal conditions of the stars has advanced, first, because of the availability of a consistent picture of the nuclear transformations that supply the large but limited amounts of energy produced inside the stars and, second, by the development of computational techniques for the study of equilibrium conditions in the interiors of stars of given mass, chemical composition, radius and surface temperature. The combination of the two approaches permits a first theoretical attack on the problems of the gradual evolution of stars. The evolutionary tracks thus found from pure theory check quite well with those derived from the observations of colour-magnitude arrays of galactic and globular star clusters, each of which represents presumably a group of stars formed within a cosmically brief interval. One of the finest achievements of our times has been the ability to predict from pure physics and pure theory the temperatures and radii for masses of gas comparable to those of the stars. We can trace by calculation alone the various stages in the evolution of a star, all the way from the initial interstellar cloud to the final white dwarf stage.

Special attention is being paid to the most massive stars, those with masses at least 10 times that of our sun, for these are the stars with the most rapid evolution —stars which are born and shine in all their glory for a brief one million years or so, then fade and disappear from the scene in an as yet unknown manner, possibly passing through a supernova stage on the way to oblivion. The radio source in Taurus and the associated Crab Nebula (Pl. IX) represent the after effects of a supernova explosion.

The study of these supergiant stars is done most advantageously in the two Star Clouds of Magellan, especially in the Large Magellanic Cloud, where they appear in large numbers and where they are easily accessible to telescopes of moderate aperture of the Southern Hemisphere observatories. In the Large Magellanic Clouds, the astronomer finds the young associations with their luminous blue-white supergiants still embedded in extensive clouds of gas, the parent nebulae, from which they were made. Pl. X, XI show in a striking manner in what ways the blue-white young stars of the Large Cloud, with their associated nebulosity, stand out against the massive background of older and fainter stars. The Large Magellanic Cloud is at a distance from the sun and earth of a little under 200,000 light years and some of

the stars that we study in it have intrinsic brightness equivalent to close to one million times that of our sun. It is worth noting that the nebular gas from which these stars were made has apparently very much the same relative proportions of the most common light elements, hydrogen, helium, oxygen, carbon and nitrogen, as we find for the stars of the Milky Way System in the vicinity of our sun. The apparent uniformity of chemical composition in our Universe is a somewhat perplexing and very interesting phenomenon.

Structure and Evolution: the Universe of Galaxies

In the introductory section we have already surveyed the present status of the Expanding Universe Theory. In this concluding section, we might ask ourselves to what extent the problems of the universe of galaxies have been solved, and what remains to be done. We shall learn that there is much room for the expansion of our knowledge when we prepare the balance sheet as of the year 1962.

We have already indicated that our weakest link in the whole structure relates to our lack of precise information on the distance scale. What we require primarily are groups of stars or nebulous objects that have their counterparts in our own galaxy or the Magellanic Clouds and that can be positively identified in the more distant galaxies. This is not an easy assignment, for the objects must be intrinsically very luminous to remain within reach of observation in remote galaxies. The apparently dependable cepheid variable of the 1930's has failed us miserably, for it comes in many guises and the period of the light variation can no longer be said to be directly indicative of its intrinsic brightness. The RR Lyrae variable stars, found in galactic globular clusters and in the outer halo of our galaxy, are of little use, for in the Andromeda Galaxy (Pl. XII, XIII) they would already appear at apparent magnitudes 25 or thereabouts, and that is too faint for their detection with the largest available telescopes. Novae, the spectacular 'new stars', fare somewhat better, but we do not have enough of them observed in our own galaxy, where near maximum light they shine with intrinsic brightnesses in the range between the equivalent of 40,000 to 250,000 times the light emitted by our sun. They are found, however, in abundance in the Andromeda Galaxy and in the long run they may prove of much assistance, especially in helping us find improved distances for the Magellanic Clouds, but again we lack a dependably calibrated distance scale for them in our galaxy. Our greatest hope seems to lie in clusters of blue-white supergiant stars and their associated nebulosity. Studies in the Large Magellanic Cloud have recently given us a fresh approach by providing us with new standards of known intrinsic brightness and with well-defined colour characteristics. We are finding methods for the positive identification of these nebulous associations in galaxies with distances up to 30 million light years, and the measurement of their total brightnesses, colours and apparent diameters promises to yield useful results.

It is a big step from a distance determination for a galaxy at 30 million light years from the sun to one 3,000 million light years away. The only practical method for finding the distance to a very remote galaxy is by identifying the object as a member of a cluster of galaxies and then estimating the distance to the cluster, a process that becomes increasingly uncertain as we turn to more distant objects. The positive identification of a galaxy as a radio source may help, because the intrinsic total optical brightness of a strong radio radiation emitting galaxy is known to be close to the equivalent of the radiation of 15,000 million suns. In practice, we often obtain a most reliable distance estimate for a remote object by measuring its redshift and by then calling upon the Hubble Constant to assign to it an approximate distance.

But that is cheating, for the primary reason for our wanting to have a good distance scale for the more remote galaxies arises from our desire to fix the Hubble Constant precisely, and we cannot have it both ways.

In the preceding paragraph we referred briefly to clusters of galaxies and these merit a little more attention at this point. There is no major controlling superstructure that dominates the universe of galaxies in the manner that the Milky Way System encompasses most of the stars known to us. Our observations reveal, for instance, no place that we can designate as the centre of the universe of galaxies. But there do exist groupings of galaxies, which range all the way from pairs, triplets . . . sextets of galaxies to modest clusters of galaxies and to clusters which count their membership in terms of hundreds of galaxies. There is at present much discussion among astronomers about the cosmological status of these clusters of galaxies. There is considerable evidence to show that these clusters of galaxies may not be permanent features and one naturally asks whence they came and what their futures may be.

The observational evidence relating to clusters of galaxies relates first of all to total masses and linear dimensions of these clusters. The astronomer who studies one of these clusters determines first as best he can the distance to the cluster. Next he counts the number of galaxies present in the cluster and, knowing the approximate masses for the various types of galaxies observed in the cluster, he obtains an estimate for the total mass. Furthermore he is able to calculate the approximate linear diameter of the cluster. From simple dynamical arguments (involving the Virial Theorem, well known to students of the kinetic theory of gases), it follows that, for a cluster of given total mass, the radius is determined by the root-mean-square of the velocities for the individual galaxies. If the cluster is stable and constant in diameter, then it follows from the Virial Theorem that the average velocity is automatically fixed once the total mass and linear diameter of the cluster are known. Hence we can check on the stability of the best-known clusters of galaxies by seeing whether or not the observed spreads of linear random velocities of cluster members come out as predicted (which would mean that all is well with the overall stability of the cluster) or different. To make a long story short, the observed spreads of random velocity always prove to be greater (by a factor 3 to 5) than those predicted from theory. If these results are substantiated by further research, then we are faced with the problem of having to accept the proposition that most groupings of galaxies are unstable. The resulting average ages of clusters and groupings of galaxies appear to be of the order of 1 to 10% of the age of the universe.

There are many observational checks which must be applied before we should accept as final the conclusion that the observed clusters of galaxies are transitory phenomena. For tremendous problems arise if we accept this conclusion. Does it mean that all clusters of galaxies and their members are of relatively recent origin? This would be the most obvious conclusion to draw from the available evidence, but it seems impossible to accept it, for among the galaxies that are most prominent in the known clusters are many that have the appearance of being very old on the cosmic scale. In a brief lecture like the present, one can only touch on some of these questions, but I might as well record here that I consider the problems relating to the evolutionary status of clusters of galaxies as the most basic puzzle we are facing today in our attempts to understand the universe of galaxies and its evolutionary status.

Another area in which we encounter a host of major problems is related to the optical identification of radio galaxies. It has been known for more than a decade

that certain galaxies are very powerful radio emitters. Five years ago, most astronomers, optical and radio alike, accepted the explanation that these were mostly pairs of galaxies in collision. In recent years some very strong objections to this interpretation have arisen. Firstly, it appears that the percentage of double and multiple galaxies among those identified optically with powerful radio sources is no greater than average. But, most important of all, there is an enormous discrepancy in dimensions. Modern interferometer techniques permit the radio astronomer to estimate with fair accuracy the angular diameters of the blobs that produce the radio emission. In the case of an optical identification with a double galaxy, the dimensions of the responsible optical pair are only one-tenth to one-fiftieth the angular dimensions of the radio galaxy. The radio astronomer is obviously not observing the radio radiation emitted by the pair of galaxies observed optically, but rather is he dealing with radiation emitted by an extended outer halo—not observed optically. The present trend is to forget about collision effects and to look for the source of the radio radiations in supernovae explosions, or possibly chains of supernova explosions. The best approach seems to be to think of the large blobs that emit the radio radiation as very tenuous clouds of high-speed particles shot out beyond the parent galaxies by supernova explosions. These high-speed particles, and their associated vast magnetic fields, presumably produce the observed intense radiation in the radio range. I might mention in passing that supernova explosions in our galaxy are supposed to produce cosmic rays, another indication that cosmic ray physicists and radio astronomers may be dealing in large measure with different observational aspects of the phenomenon of supernova explosions.

The present lecture is obviously incomplete in that it touches briefly on some important aspects of current astronomical thought, while totally omitting others of comparable or possibly greater significance. But I do hope that I may have succeeded in sketching the grandeur of the total picture that emerges. Our knowledge of the physical universe has not simply been expanding—it has literally exploded.

Explanation of Plates

Plate V—The Planet Mars. Lowell Observatory photograph.

Plate VI—The globular star cluster 47 Tucanae. Distance about 20,000 light years. Mount Stromlo Observatory photograph.

Plate VII—A region of nebulosity in the Milky Way first observed by the late Colin S. Gum. Mount Stromlo Observatory photograph.

Plate VIII—The Horse Head Nebula in Orion. Mount Wilson and Palomar Observatories photograph.

Plate IX—The Crab Nebula in Taurus. The after-effects of a supernova explosion: a strong radio source. Mount Wilson and Palomar Observatories photograph.

Plate X—Part of the Large Magellanic Cloud in ultraviolet light, showing bright nebulosity and the associated young stars. Mount Stromlo Observatory photograph.

Plate XI—Part of the Large Magellanic Cloud in infrared light, showing principally the older stars, Mount Stromlo Observatory photograph.

Plate XII—The Great Spiral in Andromeda. A general view of this galaxy (48-inch Schmidt photograph). Mount Wilson and Palomar Observatories photograph.

Plate XIII—The lower right-hand corner of Pl. XII, showing the individual stars (100-inch reflector photograph). Mount Wilson and Palomar Observatories photograph.